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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: ETL-R016
2. GOVT ACCESSION NO.: AD-A102
3. RECIPIENT'S CATALOG NUMBER: 695
4. TITLE (and Subtitle): Potential Hardware and Software Improvements of Inertial Positioning and Gravity Vector Determination
5. TYPE OF REPORT & PERIOD COVERED: Paper
6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): H. Baussus von Luetzow
8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS

LEVEL

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Engineer Topographic Laboratories, Ft. Belvoir, VA 22060
12. REPORT DATE: Aug 17 1981
13. NUMBER OF PAGES: 10
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

improvements
inertial positioning
gravity vector determination

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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F I G XVI. INTERNATIONAL CONGRESS
MONTREUX, SWITZERLAND, 1981

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POTENTIAL HARDWARE AND SOFTWARE IMPROVEMENTS OF INERTIAL POSITIONING AND GRAVITY VECTOR DETERMINATION *

H. BAUSSUS VON LUETZOW

ZUSAMMENFASSUNG

In diesem Vortrag werden der potentielle Einschluss von Kreiseln und Beschleunigungsmessern hoeherer Genauigkeit in den horizontalen Kanaelen des vertikal orientierten Inertialortsbestimmungssystems von Litton und resultierende Verbesserungen hinsichtlich Positions-und Lotabweichungsermittlung eroertert. Ferner werden Lotabweichungs-Fehlerschaetzungen mittels einfacher und hoeherer Datenreduzierungsverfahren geliefert und interessierende Beschraenkungen identifiziert.

SUMMARY

The paper discusses the potential incorporation of higher performance gyroscopes and accelerometers in the horizontal channels of Litton's local-level inertial positioning system and the resulting improvements in positioning and deflection of the vertical determination. It further provides deflection error estimates based on the use of simple and advanced data reduction methods and identifies limitations of interest.

RÉSUMÉ

Cette étude est une discussion sur l'incorporation potentielle des gyroscopes de haut rendement et des accélérometres dans les voies horizontalles du systeme inertiélle de détermination du point a niveau locale de la compagnie Litton. Cette communication fournit une évaluation de l'erreur de déflection basées sur l'emploi de méthodes fondamentalles et avancées de reduction de données. Les limites de l'intérêt dans ce sujet sont établies.

INTRODUCTION

The present Rapid Geodetic Survey System (RGSS), developed by Litton Systems, Inc. for the U.S. Army Engineer Topographic Laboratories (ETL), has the capability of determining horizontal and vertical positions, deflections of the vertical, and gravity anomalies with average rms errors of 1 m, 0.3 m, 2 arcsec, and 2 mgal, respectively, for 50 km runs under utilization of post-mission adjustments. It operates as a quasi local-level system. It thus does not require altitude damping, permits Kalman stochastic error control without great complexity under consideration of observed velocity errors at

*Invited paper, to be presented on Aug. 17, 1981.

vehicle stops, and employs effective post-mission adjustments with the aid of terminal position and gravity vector information only. Present critical hardware consists of an A-1000 vertical accelerometer, two A-200 horizontal accelerometers, and two G-300 gyroscopes. Although data utilization from repeated runs has resulted in average deflection rms errors of about 1 arcsec, the requirement of a maximum rms error of 0.5 arcsec necessitates the incorporation of higher performance gyroscopes and accelerometers. This would simultaneously achieve conventional surveying accuracy (10^{-5}).

2. SIGNIFICANCE OF HIGHER PERFORMANCE GYROSCOPES AND ACCELEROMETERS FOR POSITION AND VERTICAL DEFLECTION ERROR REDUCTION

Following the approximate elimination of the effects of constant gyro biases on positions under utilization of accurate initial and terminal coordinates, the remaining dominant error source is gyro correlated random noise. In this respect, the pertinent parameters for the G-300 instruments are a standard deviation of 0.002^{0} hr^{-1} and a correlation time of 3 hours. Another error source to be considered is the accelerometer scale factor, assumed to be constant for a test run. The standard scale factor error for the A-200 accelerometer is 0.01%. Correlated accelerometer noise is characterized by a standard deviation of 10 mgal and a correlation time of 40 minutes. Both correlated gyro random drift and correlated accelerometer measurement errors affect the accuracy of deflections of the vertical estimated from inertial data and initial and terminal deflection components, possibly augmented by corresponding geodetic azimuths. In order to achieve deflection accuracies smaller than or equal to 0.5 arcsec rms, it is, therefore, necessary to install higher performance gyros and accelerometers. A significant reduction of the two autocorrelation parameters is also a necessary prerequisite for the optimal statistical estimation of deflections of the vertical. The Litton G-1200 gyro is expected to be compatible with the stringent deflection accuracy requirement. Its random drift error is about $0.001^{0}hr^{-1}$ and its autocorrelation parameter is short. For details, reference is made to Litton [1974] and Huddle [1977a]. The A-1000 accelerometer addressed by Litton [1973,1975] has a standard scale factor error of approximately 0.005%. Correlated accelerometer noise is 2 mgal rms, equivalent to about 0.35 arcsec. As mentioned in the introduction, this instrument is already incorporated in the vertical channel of the present RGSS. In conjunction herewith, an improved velocity quantizer has been installed. These improvements have resulted in altitude errors of 0.3m rms and gravity errors of 2 mgal rms after 2-hour runs and under utilization of post-mission adjustments. Of further significance, the precision of the G-300 gyros and A-200 accelerometers, primary horizontal channel components of the present RGSS, is greater than indicated by the accuracy parameters. This has been observed by Schwarz [1979a] and by ETL after evaluation of repeated test runs during 1980. Multiple runs can also be expected to reduce the single run standard deviations associated with an advanced RGSS (ARGSS), advocated by the author in 1978.

3. BASIC METHOD FOR THE DETERMINATION OF DEFLECTIONS OF THE VERTICAL

A presentation of both Kalman error control and post-mission adjustment and of the determination of deflection components has been made by Baussus von Luetzow [1979]. With respect to position determination, Schwarz [1979b] noted that the errors increased considerably during tests in strongly mountainous terrain. This is due to the fact that under these conditions gravity anomalies and deflections of the vertical cannot be satisfactorily modeled as quasi-stationary random variables in the real time Kalman error controller. Fortunately, these inherent difficulties do not significantly affect the determination of deflections of the vertical, the detailed discussion of which requires the utilization of the local-level error differential equations, applicable to horizontal motion and restricted to land vehicles:

$$\frac{d}{dt}\hat{y} = -\frac{1}{R}\dot{y} \tag{1}$$

$$\frac{d}{dt}\hat{x} = \frac{1}{R}\dot{x} \tag{2}$$

$$\frac{d}{dt}\dot{y} = S_N\Phi_Z - g\Phi_N + g\eta + a_E \tag{3}$$

$$\frac{d}{dt}\dot{x} = -S_E\Phi_Z + g\Phi_E - g\xi + a_N \tag{4}$$

$$\frac{d}{dt}\phi_Z = \tan\phi\,\frac{\dot{y}}{R} - (\Omega_N + \rho_N\sec^2\phi)\,\hat{x} + \omega_N\Phi_E + \alpha \tag{5}$$

$$\frac{d}{dt}\phi_N = \frac{\dot{y}}{R} + \omega_Z\Phi_E + \beta \tag{6}$$

$$\frac{d}{dt}\phi_E = -\frac{\dot{x}}{R} + \omega_Z\Phi_N + \omega_N\Phi_Z + \gamma \tag{7}$$

For simplicity, the symbol δ in front of the dependent variables has been ommitted. The applicable coordinate system is evident from figure 1.

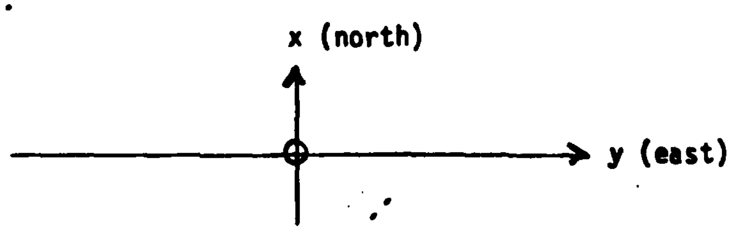

Figure 1
Applicable Coordinate System

Symbols used in the foregoing equations are with z downward:

$\hat{x}$ north angular position error

$\hat{y}$ east angular position error (for longitudes west of Greenwich)

$\dot{x}$ north velocity error

$\dot{y}$ east velocity error

α azimuth axis angular drift rate error

β north axis angular drift rate error

γ east axis angular drift rate error

g normal gravity

ϕ geographic latitude

R mean earth radius

Φ_Z azimuth platform attitude error

Φ_N platform tilt error about north axis

Φ_E platform tilt error about east axis

$g\eta$ product of g and deflection component η

$g\xi$ product of g and deflection component ξ

$S_N = \frac{dV_N}{dt}$ north acceleration of survey vehicle

$S_E = \frac{dV_E}{dt}$ east acceleration of survey vehicle

a_E correlated east accelerometer error

a_N correlated north accelerometer error

$\Omega_N = \Omega\cos\phi$ north earth rate

$\rho_N = V_E/R$ north angular rate

$\omega_N = \Omega_N + \rho_N = \Omega\cos\phi + V_E/R$ north spatial rate

$\omega_E = \rho_E = -V_N/R$ east spatial rate

$\omega_Z = \Omega_Z + \rho_Z = \Omega\sin\phi + V_E/R \cdot \mathrm{tn}\phi$ vertical spatial rate

In inertial land navigation terms involving ω_E in equations (5) and (6) are neglected in Litton's Kalman error controller. The initial conditions at time $t_0 = 0$ are

$\phi_Z^{(0)} = 0,\ \phi_N^{(0)} = \eta_0,\ \phi_E^{(0)} = \xi_0,\ \dot{x}^{(0)} = \dot{y}^{(0)} = x^{(0)} = y^{(0)} = 0.$

In the general RGSS mode of operation, position and gravity vector information is generated. The corresponding Kalman mechanization is then simplified by setting $\omega_N = \omega_Z = 0$ in equations (5)-(7) which results in the uncoupling of the horizontal channel error differential equations. This is not critical for travel periods of 2 hours.

As an example, equations (4) and (7) may then be formulated at the end of the first travel period, whence $t = t_1$,

$$\ddot{x}_1 = g\phi_{E_1} - g\xi_1 + a_{N_1} - a_{N_0} \tag{8}$$

$$\phi_{E_1} = -\frac{x_1}{R} + \int_0^{t_1} \gamma dt + \xi_0 \tag{9}$$

In eq. (8), the existence of an initial accelerometer measurement error has been taken into consideration.

The magnitude x_1 is well estimated by the observed velocity error $\dot{x}_1$. After implementation of the tilt correction $-\frac{x_1}{R}$ (est.), equations (9) and (8) read

$$\phi_{E_1}^{(1)} = -\delta_1 + \int_0^{t_1} \dot{\gamma} dt + \xi_0 \tag{10}$$

$$\ddot{x}_1^{(1)} = g\left(-\delta_1 + \int_0^{t_1} \dot{\gamma} dt\right) - g\left(\xi_1 - \xi_0\right) + a_{N_1} - a_{N_0} \tag{11}$$

The estimation error δ_1 is generally negligible.

Because of the quasi-elimination of integrated terms involving $\dot{x}$, $\dot{y}$, $\hat{x}$ in equations (5)-(7) by appropriate tilt corrections, constant gyro biases may be obtained with a high degree of approximation by a solution of these equations with $\dot{x} = \dot{y} = \hat{x} = 0$ and $\alpha = \bar{\alpha}$, $\beta = \bar{\beta}$, $\gamma = \bar{\gamma}$. It is then, according to Huddle [1977b],

$$\bar{\phi}_E = t\left(\bar{\gamma} + \bar{\beta}\frac{\Omega_z}{2}t - \bar{\alpha}\frac{\Omega_N}{2}t\right) \tag{12}$$

$$\bar{\phi}_N = t\left(-\bar{\gamma}\frac{\Omega_z}{2}t + \bar{\beta}\right) \tag{13}$$

$$\bar{\phi}_Z = t\left(\bar{\gamma}\frac{\Omega_N}{2}t + \bar{\alpha}\right) \tag{14}$$

Under consideration of terminal deflection and azimuth closure errors, it is possible to compute $\bar{\alpha}$, $\bar{\beta}$, $\bar{\gamma}$ from

$$\bar{\Phi}_E(t_n) = \xi_{\text{ estimated}}(t_n) - \xi_{\text{ observed}}(t_n) \quad (15)$$

$$\bar{\Phi}_N(t_n) = \eta_{\text{ estimated}}(t_n) - \eta_{\text{ observed}}(t_n) \quad (16)$$

$$\bar{\Phi}_Z(t_n) = A_{\text{ estimated}}(t_n) - A_{\text{ observed}}(t_n) \quad (17)$$

where A designates geodetic azimuth.

Examination of equations (12)-(14) reveals that in moderate latitudes there exists relatively small coupling for time intervals not exceeding 2 hours. For this reason, linear approximations $\bar{\Phi}_E \approx \bar{\gamma}t$ and $\bar{\Phi}_N \approx \bar{\beta}t$ have been used with success. Highly accurate deflection determinations, accomplished by means of an ARGSS, would, however, require consideration of a terminal azimuth error.

For $t = t_i$, equation (11) may be formulated with $\delta_i = 0$ as

$$\ddot{x}(t_i) = \ddot{x}_i = g\bar{\Phi}_{Ei} - g\,(\xi_i - \xi_o) + g\int_o^{t_i} (\gamma - \bar{\gamma})dt + a_{N_i} - a_{N_o} \quad (18)$$

$$\ddot{x}(t_n) = \ddot{x}_n = g\bar{\Phi}_{En} - g\,(\xi_n - \xi_o) + g\int_o^{t_n} (\gamma - \bar{\gamma})dt + a_{N_n} - a_{N_o} \quad (19)$$

Equations (12) and (19) show that the computation of $\bar{\Phi}_{Ei}$ is to the first order associated with an error

$$\delta\bar{\Phi}_{Ei} = -\frac{t_i}{t_n}\left[\, g\int_o^{t_n}(\gamma - \bar{\gamma})dt + a_{N_n} - a_{N_o}\right] \quad (20)$$

The basic solution for the prime deflection of the vertical from equations (18) and (19) is

$$\boxed{\xi_i = \left(\xi_o + \bar{\Phi}_{Ei} - \frac{\ddot{x}_i}{g}\right) + \frac{a_{N_i} - a_{N_o}}{g} - \frac{t_i}{t_n}\,\frac{a_{N_n} - a_{N_o}}{g} + \int_o^{t_i}(\gamma - \bar{\gamma})dt - \frac{t_i}{t_n}\int_o^{t_n}(\gamma - \bar{\gamma})dt} \quad (21)$$

Equation (21) may be supplemented by

$$\delta\xi_i = \delta\xi_o + \frac{t_i}{t_n}(\delta\xi_e - \delta\xi_o) - (\phi_{S_i} - \frac{t_i}{t_n}\phi_{S_n}) \tag{22}$$

to account for astrogeodetic deflection errors and accelerometer bias errors. For a straight traverse, the last term in eq. (22) tends to cancel out.

The rms deflection error $\sigma_\xi(t_i)$ can be computed by covariance analysis involving the terms without parentheses in eq. (21). Under inclusion of the first two terms of eq. (22) it is

$$\text{var } \xi_i = \text{var } a_i + \text{var } \gamma_i + (1 - \frac{t_i}{t_n})^2 \text{ var } \xi_o + (\frac{t_i}{t_n})^2 \text{ var } \xi_n \tag{23}$$

where var a_i is the accelerometer-induced variance and var γ_i designates the gyro-induced variance. Under consideration of present RGSS parameters, identified in section 2, the rms deflection error σ_{ξ_i} is approximately presented in Figure 2.

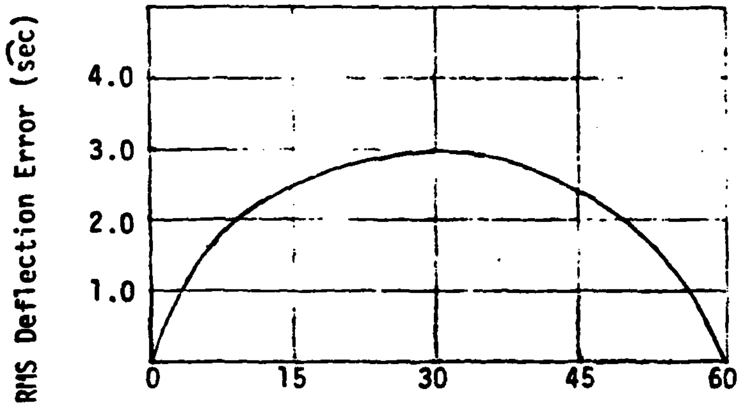

Figure 2

Approximate RMS Deflection Error as Function of Travel Time

The variation of normal gravity g with altitude is not critical in terrestrial applications. The scale factor-generated error does not vanish with respect to L-shaped traverses. It is, however, relatively small for travel times not exceeding 2 hours. Heading sensitivity induced by significant azimuth changes appears to be somewhat critical and may require empirical corrections. Schwarz [1979b] discussed the impact of heading sensitivity on positioning and concluded that error reductions may be achieved by a modified smoothing procedure. The problem is more intricate in the case of deflection determinations. The use of static accelerometer measurements in conjunction with initial and terminal deflections together with a simplified Kalman filter originated with Huddle [1977a]. The above analytical presentation is one of several quasi-linearization techniques according to the terminology of Schwarz [1980]. It may be refined by a finite difference solution of the system differential equations (1)-(7) with ϕ = const. with or without periodic filter corrections. This would result in weight factor expressions as a function of time involving the generating variables $\xi = \xi[x(t), y(t)]$, $\eta = \eta[x(t), y(t)]$, $a_E - a_{E_0}$, $a_N - a_{N_0}$, α, β, and γ. Approximate constant vehicle velocities would simplify the computations. A matrix solution involving all unknown ξ's and η's would then replace the independent single component solutions.

4. ADVANCED METHOD FOR DEFLECTION DETERMINATION

Equation (21) under inclusion of the first two terms of eq. (22) or a comparable refined solution identified in section 3 may be formulated as

$$\xi_i = \hat{\xi}_i + n_i \tag{24}$$

where $\xi_i = \xi_o + \overline{\Phi}_{Ei} - \frac{\ddot{x}_i}{g}$ is a message variable, $\hat{\xi}_i$ is a signal variable, and the remaining terms denote a noise variable - n_i. The collocation method in physical geodesy permits in semi-flat terrain the estimation

$$\hat{\xi}_e = \sum_i a_i(\hat{\xi}_i + n_i) = A_i(\Xi_i + N_i) \tag{25}$$

where A_i is the matrix of regression coefficients a_i to be computed. It is then in matrix form, with bars indicating covariances,

$$\overline{\hat{\xi}_e \hat{\Xi}_k} = A_i(\overline{\Xi_i \Xi_k} + \overline{N_i N_k}), \qquad \{{i \atop k}\} = 0, 1, \ldots n \tag{26}$$

The solution for the regression coefficient matrix follows as

$$A_i = \overline{\hat{\xi}_e \hat{\Xi}_k}\ (\overline{\hat{\Xi}_i \hat{\Xi}_k} + \overline{N_i N_k})^{-1} \tag{27}$$

Due to the sizable gyro and accelerometer correlation times associated with the present RGSS, the advanced method characterized by equations (25) and (27) does not provide significantly better deflection estimates. Considerably improved estimates would, however, result under utilization of intermediate deflection constraints. In the context of an ARGSS, i.e., under consideration of very short correlation times, the advanced method may be expected to yield better estimates. In addition, it constitutes the statistical framework for an optimal area solution under utilization of data relating to several traverses. The computation of topographic corrections and of spatial covariance functions for applications in strongly mountainous terrain has been presented by Baussus von Luetzow [1981]. Alternatively, it would be necessary to conduct repeated runs. In this way, rms deflection errors not to exceed 0.35 arcsec are within the reach of an ARGSS.

5. CONCLUSION

The incorporation of identified or other higher performance gyros and accelerometers and of improved velocity quantizers in Litton's RGSS would result in an ARGSS. Non-linear gyro bias corrections, elimination of errors caused by gyro heading sensitivity, and advanced data reduction techniques or repeated runs are then expected to facilitate deflection determinations with standard errors not to exceed 0.35 arcsec for a travel time of 2 hours or about 60 km distance. As a by-product, conventional surveying accuracy would be achieved. Deflection changes $\xi-\xi_o$ and $\eta-\eta_o$ with standard errors of the order 0.1 arcsec for the same travel time and vehicle speed would require supplementation by a high-performance gravity gradiometer.

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